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NN Final-State Interaction in the Helicity Dependence of Inclusive π^- Photoproduction from the Deuteron*)

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The helicity dependence of the inclusive π^- photoproduction reaction from the deuteron in the $\Delta(1232)$-resonance region is investigated with inclusion of final-state nucleon-nucleon rescattering (NN-FSI). For the elementary π-production operator an effective Lagrangian model which includes the standard pseudovector Born terms and a contribution from the Δ-resonance is used. The half-off-shell NN-scattering matrix is obtained from a separable representation of a realistic NN-interaction. The differential polarized cross-section difference for parallel and antiparallel helicity states is predicted and compared with experiment. We find that the effect of NN-FSI is much less important in the helicity difference than in the previously studied unpolarized differential cross section. Furthermore, the contribution of $\vec{d}(\vec{\gamma},\pi^-)pp$ to the deuteron spin asymmetry is explicitly evaluated with inclusion of NN-FSI. It has been found that the effect of NN-FSI is much larger in the asymmetry than in the total cross section, and this leads to an appreciable reduction of the spin asymmetry in the Δ-region. Inclusion of such effect also leads to improved and quite satisfactory agreement with existing experimental data.

§1. Introduction

A very interesting topic in intermediate energy nuclear physics is concerned with the quasi-free pion production reaction in nuclei, which is governed by three main mechanisms: (i) the elementary amplitudes of the four pion production channels possible from the nucleon, (ii) the Fermi motion of the protons and neutrons inside the nucleus, and (iii) the interaction between the final-state hadrons. The investigation of pion photo- and electro-production has the potential to become an important topic in meson physics, because many important features of electromagnetic and hadronic reactions can be studied through these processes. Interest in this topic has increased mainly as a result of the construction of new high-duty continuous electron beam machines such as MAMI in Mainz and ELSA in Bonn.

The particular interest in pion photo-production reaction from the deuteron is due to the fact that the simple and well known deuteron structure allows one to obtain information regarding the production process from the neutron, which otherwise is difficult to obtain because of the lack of free neutron targets. The earliest calculations for pion photo-production from the deuteron were performed using the impulse approximation (IA).[1),2)] Approximate treatments of final-state interaction (FSI) effects within a diagrammatic approach have been reported in Refs.[3),4),5)] The

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authors of those works noted that the FSI effects are quite small for the charged-pion production channels in comparison to the neutral one. Photo-production of pions from the deuteron has been investigated with the spectator nucleon model,[6] ignoring all kinds of FSI and two-body processes. The NN-FSI is considered in Ref.,[7] and good agreement with experiment was obtained. The influence of final-state NN- and πN-rescattering on the unpolarized cross sections is investigated in Ref.[8] There, it is found that πN-rescattering is much less important (in general negligible) than NN-rescattering. Inclusion of such effects leads to good agreement with experiment. The role of the $N\Delta$-FSI in pion photo-production from the deuteron is investigated in Ref.[9] It has been shown that full calculations with the off-shell amplitudes of NN- and $N\Delta$-FSI are necessary to obtain a quantitative description of the cross sections.

To this time, most of calculations have treated only unpolarized observables, like the differential and total cross sections. These cross sections provide information only regarding the sum of the absolute squares of the amplitudes, whereas the polarization observables allow extraction of more information. Observables with a polarized photon beam and/or polarized deuteron target have not been throughly investigated. The particular interest in these observables is due to the fact that a series of measurements of the polarization observables in photo-production reactions have already been carried out and are planned at different laboratories. The GDH collaboration has undertaken a joint effort to experimentally verify the Gerasimov-Drell-Hearn (GDH) sum rule, measuring the difference between the helicity components in the total and differential photo-absorption cross sections. Our goal is to carry out an analysis of these experimental measurements.

Recently, polarization observables for incoherent pion photo-production reaction from the deuteron have been studied in Refs.[10],[11],[12],[13],[14],[15] The π^--production channel has been studied within a diagrammatic approach[10] including NN- and πN-rescattering. In that work, predictions for the analyzing powers connected to beam and target polarization and to the polarization of one of the final protons are presented. In a previous evaluation,[11] special emphasis was given to the beam-target spin asymmetry and the GDH sum rule. Single- and double-spin asymmetries for incoherent pion photo-production reaction from the deuteron are predicted in Refs.[12],[13],[14] without any FSI effects. The target tensor analyzing powers of the $d(\gamma, \pi^-)pp$ reaction have been studied in the plane wave impulse approximation.[15] Most recently, our evaluation[11] was extended to higher energies in Ref.[16] with additional inclusion of two-pion and eta production.

As a further step in this study, we investigate in this paper the influence of NN FSI effects on the polarized differential and total cross sections with respect to parallel and antiparallel spins of the photon and the deuteron in the reaction $\gamma d \rightarrow \pi^- pp$. Our second point of interest is to analyze the recent experimental data from the GDH collaboration.[17] With respect to the interactions in the final two-body subsystems, only the NN-rescattering is taken into account, because πN-rescattering is considered negligible.[7],[8]

In §2, the model for the elementary $\gamma N \rightarrow \pi N$ and $NN \rightarrow NN$ reactions that serves as an input for the reaction from the deuteron is briefly reviewed. In §3, we introduce the general formalism for incoherent pion photo-production from the

deuteron. The separate contributions of the IA and the NN-rescattering to the transition matrix are described in that section. Details of the actual calculation and the results are presented and discussed in §4. Finally, a summary and conclusions are given in §5.

§2. The elementary $\gamma N \to \pi N$ and $NN \to NN$ reactions

Pion photo-production reaction from the deuteron is governed by basic two-body processes, namely pion photo-production from a nucleon and hadronic two-body scattering reactions. For the latter, only nucleon-nucleon scattering is considered in this work. As mentioned in the introduction, πN-rescattering is found to be negligible, and therefore it is not considered in the present calculation.

The starting point for the construction of an operator for pion photo-production in the two-nucleon space is the elementary pion photo-production operator acting on a single nucleon, i.e. $\gamma N \to \pi N$. In the present work we examine various observables for pion photo-production reaction from the free nucleon using, as in our previous work,[8] the effective Lagrangian model developed by Schmidt et al.[6] The main advantage of this model is that it has been constructed to give a realistic description of the $\Delta(1232)$-resonance region. It is also given in an arbitrary frame of reference and allows a well defined off-shell continuation, as required for studying pion production reactions from nuclei. This model consists of the standard pseudovector Born terms and the contribution of the $\Delta(1232)$-resonance. For further details with respect to the elementary pion photo-production operator, we refer the reader to Ref.[6] As shown in Figs. 1 - 3 of our previous work,[8] the results of our calculations for the elementary process are in good agreement with recent experimental data, as well as with other theoretical predictions. This gives a clear indication that this elementary operator is quite satisfactory for our purpose, namely to incorporate it into the pion photo-production reaction from the deuteron.

For nucleon-nucleon scattering in the NN-subsystem, we use in this work a specific class of separable potentials[18] which historically have played and still play a major role in the development of few-body physics and also fit the phase shift data for NN-scattering. The EST method[19] for constructing separable representations of modern NN potentials has been applied by the Graz group[18] to cast the Paris potential[20] into a separable form. This separable model is most widely used in the case of the πNN system (see, for example, Ref.[21] and references therein). Therefore, for the present study of the influence of NN-rescattering, this model is appropriate.

§3. π-photoproduction from the deuteron

The formalism of incoherent pion photo-production reaction from the deuteron is presented in detail in our previous work.[8] Here, we briefly recall the necessary notation and definitions. As shown in Ref.,[22] the general expression for the unpolarized cross section is given by

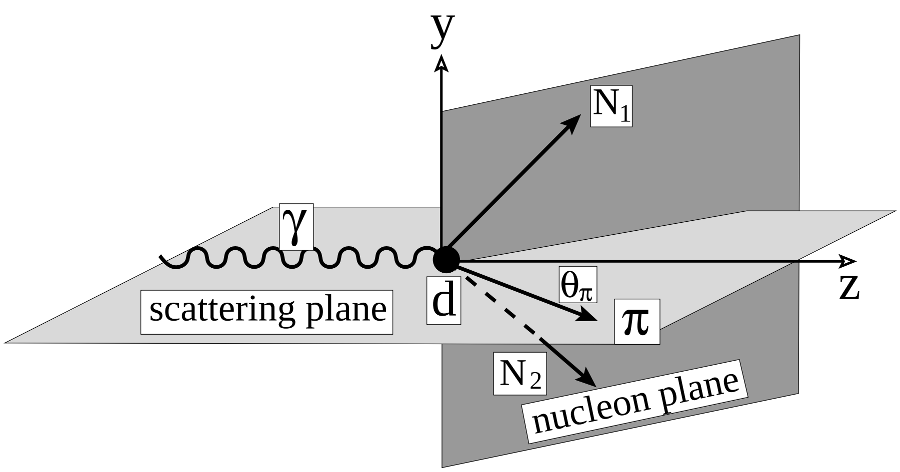

Fig. 1. Kinematics in the laboratory system for pion photo-production from the deuteron.

$$d\sigma = \frac{\delta^4(k+d-p_1-p_2-q)M_N^2 d^3p_1 d^3p_2 d^3q}{96(2\pi)^5|\vec{v}_\gamma - \vec{v}_d|\omega_\gamma E_d E_1 E_2 \omega_q} \sum_{s\,m\,t\,,m_\gamma\,m_d} \left|\mathcal{M}^{(t\,\mu)}_{s\,m\,m_\gamma\,m_d}(\vec{p}_1,\vec{p}_2,\vec{q},\vec{k},\vec{d})\right|^2 , \tag{3·1}$$

where $k = (\omega_\gamma, \vec{k})$, $d = (E_d, \vec{d})$, $q = (\omega_q, \vec{q})$, $p_1 = (E_1, \vec{p}_1)$ and $p_2 = (E_2, \vec{p}_2)$ denote the 4-momenta of the photon, deuteron, pion and two nucleons, respectively. Furthermore, m_γ denotes the photon polarization, m_d the spin projection of the deuteron, s and m the total spin and projection of the two outgoing nucleons, respectively, t their total isospin, μ the isospin projection of the pion, and $\vec{v}_\gamma$ and $\vec{v}_d$ the velocities of the photon and deuteron, respectively. The transition amplitude is denoted by $\mathcal{M}$. Covariant state normalization according to the convention of Ref.[22] is assumed.

This expression is evaluated in the lab or deuteron rest frame. A right-handed coordinate system is chosen, where the z-axis is defined by the photon momentum $\vec{k}$ and the y-axis by $\vec{k} \times \vec{q}$. The scattering plane is defined by the momenta of photon $\vec{k}$ and pion $\vec{q}$, whereas the momenta of the outgoing nucleons $\vec{p}_1$ and $\vec{p}_2$ define the nucleon plane (see Fig. 1). As independent variables, the pion momentum q, its angles θ_π and ϕ_π, the polar angle $\theta_{p_{NN}}$ and the azimuthal angle $\phi_{p_{NN}}$ of the relative momentum $\vec{p}_{NN}$ of the two outgoing nucleons are chosen. The total and relative momenta of the final NN-system are defined by $\vec{P}_{NN} = \vec{p}_1 + \vec{p}_2 = \vec{k} - \vec{q}$ and $\vec{p}_{NN} = \frac{1}{2}(\vec{p}_1 - \vec{p}_2)$, respectively.

Integrating over the pion momentum q and over $\Omega_{p_{NN}}$, one obtains the semi-inclusive differential cross section of pion photo-production from the deuteron, where only the final pion is detected without analyzing its energy,

$$\frac{d\sigma}{d\Omega_\pi} = \int_0^{q_{\max}} dq \int d\Omega_{p_{NN}} \frac{\rho_s}{6} \sum_{s\,m\,t\,m_\gamma\,m_d} \left|\mathcal{M}^{(t\,\mu)}_{s\,m\,m_\gamma\,m_d}(\vec{p}_{NN},\vec{q},\vec{k})\right|^2 , \tag{3·2}$$

where ρ_s denotes the phase space factor [see Eq. (7) in Ref.[8] for its definition].

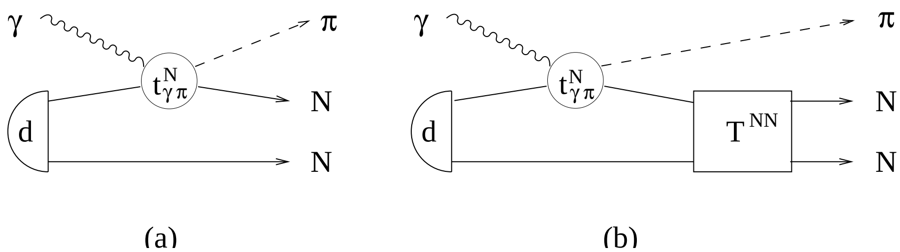

Fig. 2. Diagrammatic representation of pion photo-production from the deuteron including NN-rescattering in the final state: (a) impulse approximation (IA) and (b) NN-rescattering.

The general form of the photo-production transition matrix is given by

$$\mathcal{M}^{(t\mu)}_{smm_\gamma m_d}(\vec{k},\vec{q},\vec{p_1},\vec{p_2}) = {}^{(-)}\langle \vec{q}\,\mu, \vec{p_1}\vec{p_2}\,s\,m\,t-\mu|\epsilon_\mu(m_\gamma)J^\mu(0)|\vec{d}\,m_d\,00\rangle\,, \quad (3\cdot3)$$

where $J^\mu(0)$ denotes the current operator. The outgoing πNN scattering state is approximated in this work by

$$|\vec{q}\,\mu, \vec{p_1}\vec{p_2}\,s\,m\,t-\mu\rangle^{(-)} = |\vec{q}\,\mu, \vec{p_1}\vec{p_2}\,s\,m\,t-\mu\rangle + G_0^{\pi NN(-)}\,T^{NN}|\vec{q}\,\mu, \vec{p_1}\vec{p_2}\,s\,m\,t-\mu\rangle\,, \quad (3\cdot4)$$

where $|\vec{q}\,\mu, \vec{p_1}\vec{p_2}\,s\,m\,t-\mu\rangle$ denotes the free πNN plane wave, $G_0^{\pi NN(-)}$ the free πNN propagator, and T^{NN} the reaction operator for NN-scattering. Thus, the total transition matrix element in this approximation reads

$$\mathcal{M}^{(t\mu)}_{smm_\gamma m_d} = \mathcal{M}^{(t\mu)\,IA}_{smm_\gamma m_d} + \mathcal{M}^{(t\mu)\,NN}_{smm_\gamma m_d}\,. \quad (3\cdot5)$$

A graphical representation of the transition matrix is given in Fig. 2.

As shown in Ref.,[8] the matrix element in the IA is given by the expression

$$\mathcal{M}^{(t\mu)\,IA}_{smm_\gamma m_d}(\vec{k},\vec{q},\vec{p}_1,\vec{p}_2) = \sqrt{2}\sum_{m'}\langle sm,\,t-\mu|\Big(\langle\vec{p}_1|t_{\gamma\pi}(\vec{k},\vec{q})|-\vec{p}_2\rangle\tilde{\Psi}_{m',m_d}(\vec{p}_2)$$
$$-(-)^{s+t}(\vec{p}_1\leftrightarrow\vec{p}_2)\Big)\,|1m',\,00\rangle\,, \quad (3\cdot6)$$

where $t_{\gamma\pi}$ denotes the elementary production amplitude from the free nucleon and $\widetilde{\Psi}_{m,m_d}(\vec{p})$ is given by

$$\widetilde{\Psi}_{m,m_d}(\vec{p}) = (2\pi)^{\frac{3}{2}}\sqrt{2E_d}\sum_{L=0,2}\sum_{m_L} i^L\,C^{L11}_{m_L m m_d}\,u_L(p)Y_{Lm_L}(\hat{p})\,. \quad (3\cdot7)$$

For the radial deuteron wave function $u_L(p)$, the Paris potential[23] is used.

For the NN-rescattering contribution, one obtains[8]

$$\mathcal{M}^{(t\mu)\,NN}_{smm_\gamma m_d}(\vec{k},\vec{q},\vec{p}_1,\vec{p}_2) = \sum_{m'}\int d^3\vec{p}\,'_{NN}\sqrt{\frac{E_1E_2}{E_1'E_2'}}\,\widetilde{\mathcal{R}}^{NN,t\mu}_{smm'}(W_{NN},\vec{p}_{NN},\vec{p}\,'_{NN})$$
$$\times\,\frac{M_N}{\widetilde{p}^{\,2}-p'^{\,2}_{NN}+i\epsilon}\mathcal{M}^{(t\mu)\,IA}_{sm',m_\gamma m_d}(\vec{k},\vec{q},\vec{p}\,'_1,\vec{p}\,'_2)\,, \quad (3\cdot8)$$

where $\vec{p}\,'_{NN} = \frac{1}{2}\,(\vec{p}\,'_1 - \vec{p}\,'_2)$ denotes the relative momentum of the interacting nucleons in the intermediate state, W_{NN} is the invariant mass of the NN-subsystem, $\vec{p}\,'_{1/2} = \pm\vec{p}\,'_{NN} + (\vec{k}-\vec{q})/2$ and $E'_{1/2}$ are the momenta and the corresponding on-shell energies of the two nucleons in the intermediate state, respectively, and $\widetilde{p}^{\,2} = M_N(E_{\gamma d} - \omega_\pi - 2M_N - (\vec{k}-\vec{q})^2/4M_N)$, with $E_{\gamma d} = M_d + \omega_\gamma$. The conventional NN-scattering matrix $\widetilde{\mathcal{R}}^{NN,\,t\mu}_{smm'}$ is introduced with respect to noncovariantly normalized states. It is expanded in terms of the partial wave contributions $\mathcal{T}^{NN,\,t\mu}_{Js\ell\ell'}$ as

$$\widetilde{\mathcal{R}}^{NN,\,t\mu}_{smm'}(W_{NN}, \vec{p}_{NN}, \vec{p}\,'_{NN}) = \sum_{J\ell\ell'} \mathcal{F}^{NN,\,Js}_{\ell\ell'\,mm'}(\hat{p}_{NN}, \hat{p}\,'_{NN}) \times \mathcal{T}^{NN,\,t\mu}_{Js\ell\ell'}(W_{NN}, p_{NN}, p'_{NN})\,, \tag{3·9}$$

where the purely angular function $\mathcal{F}^{NN,\,Js}_{\ell\ell' mm'}(\hat{p}_{NN}, \hat{p}\,'_{NN})$ is defined by

$$\mathcal{F}^{NN,\,Js}_{\ell\ell' mm'}(\hat{p}_{NN}, \hat{p}\,'_{NN}) = \sum_{Mm_\ell m_{\ell'}} C^{\ell sJ}_{m_\ell mM}\, C^{\ell' sJ}_{m_{\ell'} m'M}\, Y^\star_{\ell m_\ell}(\hat{p}_{NN}) Y_{\ell' m_{\ell'}}(\hat{p}\,'_{NN})\,. \tag{3·10}$$

The necessary half-off-shell NN-scattering matrix $\mathcal{T}^{NN,\,t\mu}_{Js\ell\ell'}$ was obtained from the separable representation of a realistic NN-interaction[18)] which gives a good description of the corresponding phase shifts. Explicitly, all partial waves with total angular momentum $J \leq 3$ have been included.

§4. Results and discussion

The discussion of our results is divided into two parts. First, we discuss the influence of the NN-FSI effect on the polarized differential cross-section difference $(d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A$ for the parallel and antiparallel helicity states by comparing the pure IA with the inclusion of NN-rescattering in the final state. Furthermore, we compare our results with recent experimental data from the GDH collaboration.[17)] In the second part, we consider the polarized total cross sections for circularly polarized photons on a target whose spin is parallel σ^P and antiparallel σ^A to the photon spin. The contribution of $\vec{\gamma}\vec{d} \to \pi^- pp$ to the spin response of the deuteron, i.e., the asymmetry of the total photo-absorption cross section with respect to parallel and antiparallel spins of photon and deuteron, has been explicitly evaluated over the range of the $\Delta(1232)$-resonance with inclusion of final-state NN-rescattering.

4.1. *The helicity difference* $(d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A$

We begin the discussion by presenting our results for the differential polarized cross-section difference for parallel $(d\sigma/d\Omega_\pi)^P$ and antiparallel $(d\sigma/d\Omega_\pi)^A$ helicity states in pure IA and with NN-rescattering, as shown in Fig. 3 as a function of the emission pion angle in the laboratory frame at several values of the photon lab energy. It is readily seen that NN-rescattering—the difference between the dashed and the solid curves—is quite small, and indeed almost completely negligible at pion backward angles. The reason for this stems from the fact that in charged-pion production, $^3S_1$-contribution to the NN final state is forbidden. In order to make a

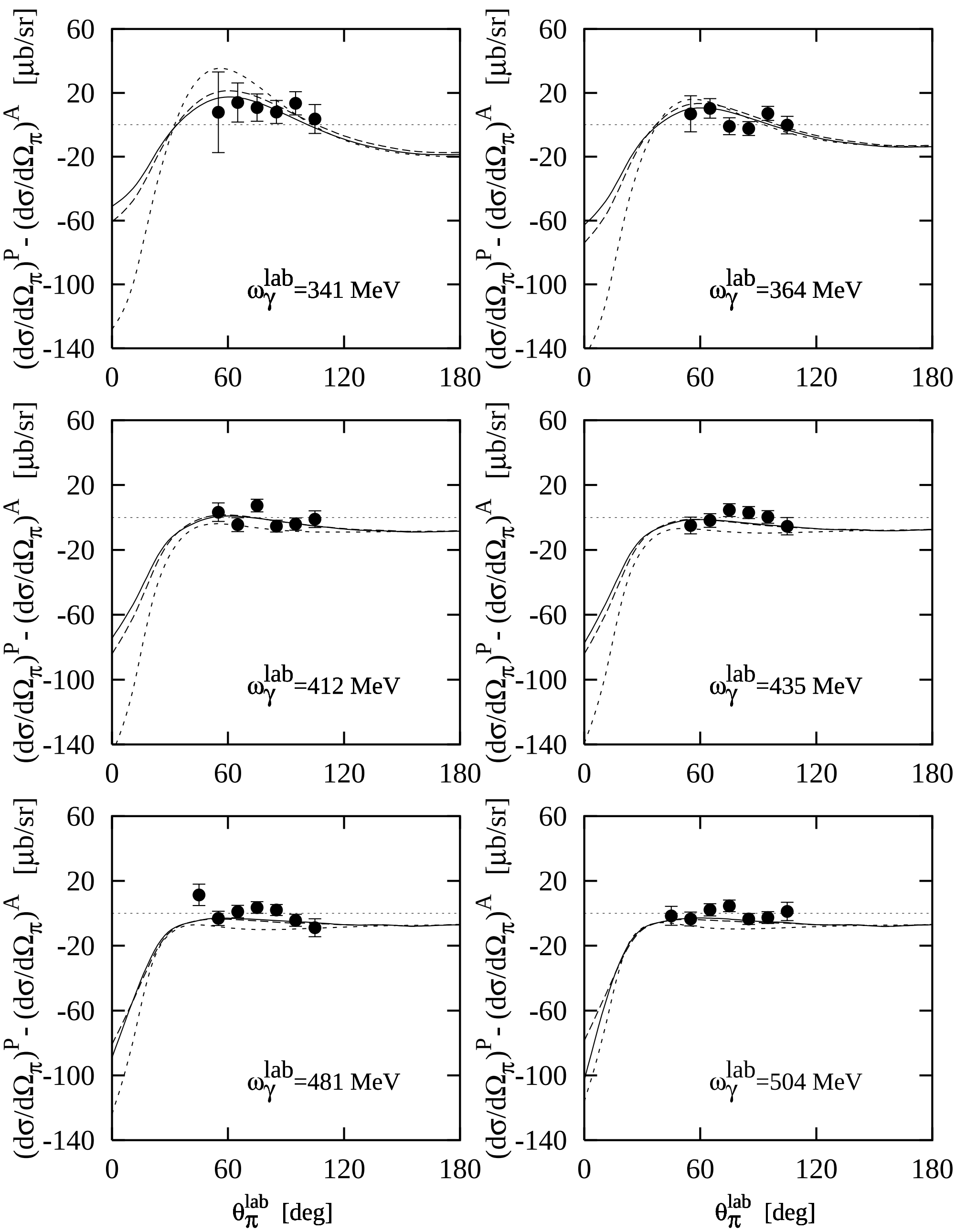

Fig. 3. The differential polarized cross-section difference $(d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A$ for $\vec{\gamma}\vec{d} \to \pi^- pp$ for the parallel $(d\sigma/d\Omega_\pi)^P$ and antiparallel $(d\sigma/d\Omega_\pi)^A$ helicity states as a function of the pion angle in the laboratory frame in comparison with recent measurements presented in Ref.[17] at different values of the photon lab energy. Dashed curves: IA; solid curves: IA+NN-rescattering; dotted curves: predictions for π^- production from the free neutron, i.e., $\vec{\gamma}\vec{n} \to \pi^- p$.

more detailed and quantitative evaluation of NN-FSI with respect to the differential polarized cross-section difference, we display in Fig. 4 the relative effect by plotting the ratio of the corresponding cross-section difference to those for the IA, i.e.,

$$\frac{(\Delta d\sigma)^{IA+NN}}{(\Delta d\sigma)^{IA}} = \frac{\left[(\frac{d\sigma}{d\Omega_\pi})^P - (\frac{d\sigma}{d\Omega_\pi})^A\right]^{IA+NN}}{\left[(\frac{d\sigma}{d\Omega_\pi})^P - (\frac{d\sigma}{d\Omega_\pi})^A\right]^{IA}}. \tag{4·1}$$

It is seen that the major contribution from NN-FSI appears at forward pion angles. This contribution is much less important in the differential polarized cross-section difference than in the previously studied unpolarized differential cross sections. (Compare with Fig. 13 in Ref.[8]) It has been found that NN-FSI reduces the unpolarized differential cross section by about 15% at $\theta_\pi = 0°$.[8] The magnitude of this reduction decreases rapidly with increasing pion angle.

By comparing the results for the difference $(d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A$ in the case of $\vec{\gamma}\vec{d} \rightarrow \pi^- pp$ (solid curves in Fig. 3) with those in the case of the free $\vec{\gamma}\vec{n} \rightarrow \pi^- p$ (dotted curves in Fig. 3), we see that a large correction is needed to go from the bound deuteron to the free neutron case. The difference between the two results decreases to a tiny effect at backward angles. Figure 3 also gives a comparison of our results for the helicity difference with the experimental data from the GDH collaboration.[17] It is obvious that quite satisfactory agreement with experiment is achieved. An experimental check of the helicity difference at extreme forward and backward pion angles is needed. Also, an independent check in the framework of effective field theory would be very interesting.

4.2. *Polarized total cross sections*

Here, we discuss the results for the polarized total cross sections in the case of the IA alone and with the NN-FSI effect. They are presented in Fig. 5, where the left top panel displays the total photo-absorption cross section σ^P for circularly polarized photons impinging on a target with spin parallel to the photon spin, the right top panel displays that for antiparallel spins of photon and target σ^A, the left bottom panel displays the spin asymmetry $\sigma^P - \sigma^A$, and the right bottom panel displays the results for the unpolarized total cross section in comparison with the experimental data from Refs.[24] (ABHHM),[25] (Frascati) and[26] (Asai). For comparison, we also depict in the same figure the results for π^- production from the free neutron target by the dotted curves. In order to see more clearly the relative size of the interaction effect, we have plotted in Fig. 6 the ratios with respect to the IA.

We find for the cross sections σ^P and σ^A, the spin asymmetry $\sigma^P - \sigma^A$, and for the unpolarized total cross section of the nucleon and the deuteron qualitatively similar behaviour, although for the deuteron, the maxima and minima are smaller and also slightly shifted toward higher energies. Furthermore, in the case of σ^P, a large deviation between the results for the IA and the elementary reaction—the difference between the dashed and the dotted curves—is seen because of the Fermi motion and FSI, whereas for σ^A the difference is smaller. The NN-FSI effect appears mainly in σ^P. The left bottom panel in Fig. 5 shows that the helicity difference of

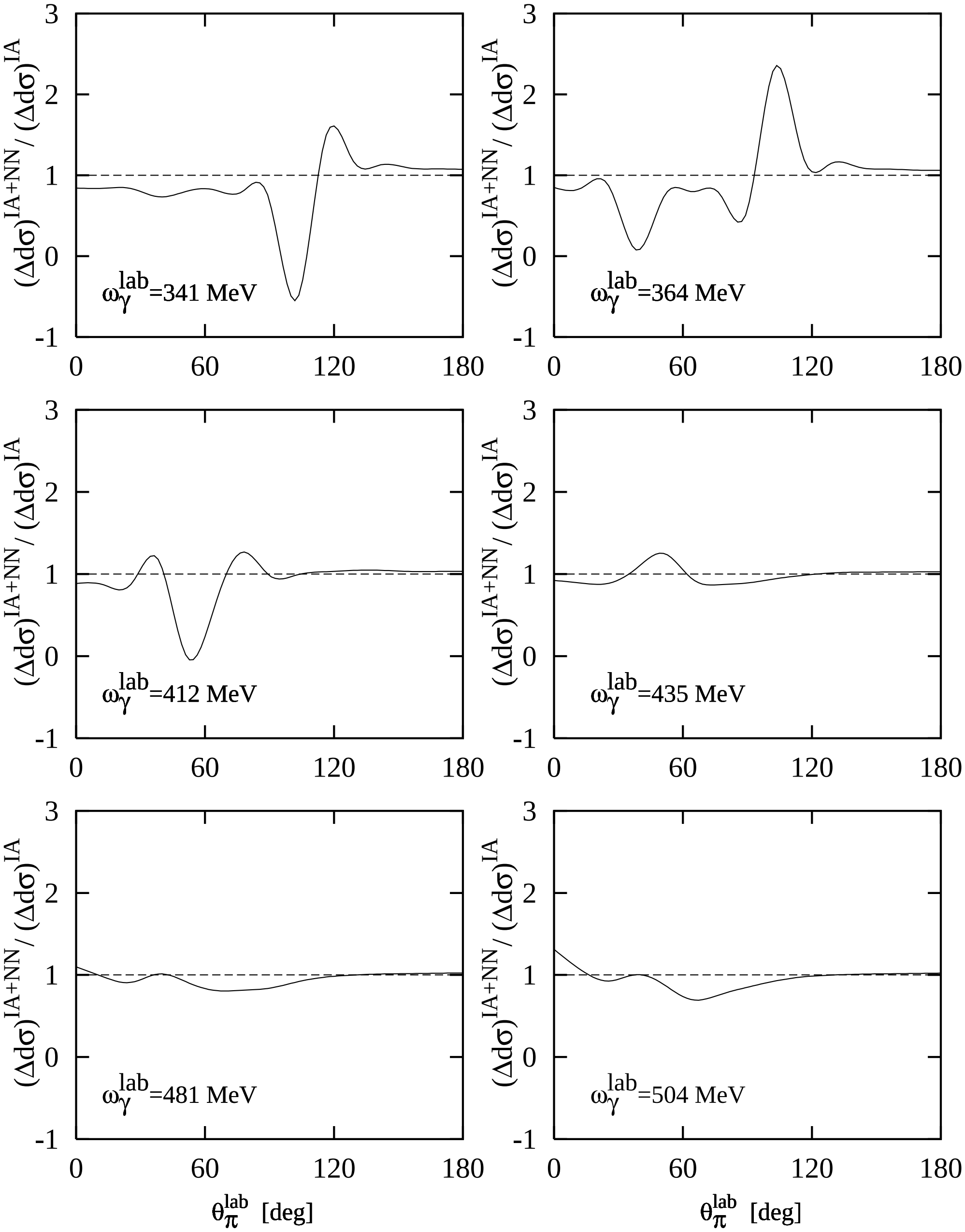

Fig. 4. The ratio $(\Delta d\sigma)^{IA+NN}/(\Delta d\sigma)^{IA}$ [see Eq. (4·1) for its definition] as a function of the pion angle in the laboratory frame for several photon lab energies.

the total cross section $(\sigma^P - \sigma^A)$ starts out negative due to the E_{0+} multipole, which is dominant in the threshold region and has a strong positive contribution due to the M_{1+} multipole, which is dominant in the $\Delta(1232)$-resonance region. It is also clear that FSI leads to a strong reduction of the spin asymmetry in the energy region of the $\Delta(1232)$-resonance. This reduction becomes about 35 μb at its

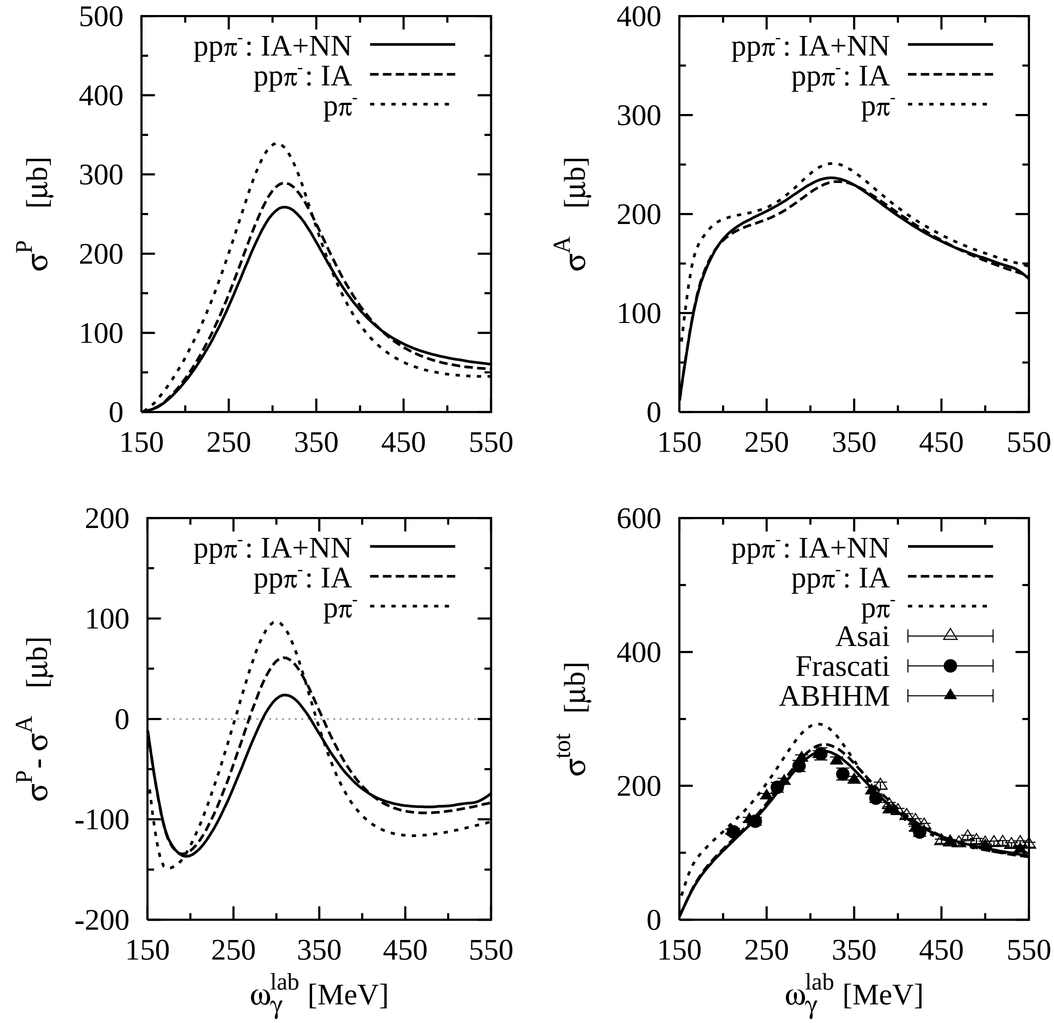

Fig. 5. The total photo-absorption cross sections for circularly polarized photons impinging on a target with spin parallel σ^P (upper left part) and antiparallel σ^A (upper right part) to the photon spin for $\vec{\gamma}\vec{d} \rightarrow \pi^- pp$ as functions of the photon lab energy. The lower part displays the difference $\sigma^P - \sigma^A$ (lower left part) and the unpolarized total cross section (lower right part). The experimental data are from Refs.[24] (ABHHM),[25] (Frascati) and[26] (Asai). The identification of the curves is the same as in Fig. 3.

maximum. Thus, the IA is not a reasonable approximation, as in the case of the unpolarized total cross section. Moreover, already the IA deviates significantly from the corresponding nucleon quantities. It is also obvious that σ^P is much larger than σ^A because of the Δ-excitation.

For the unpolarized total cross section displayed in the bottom right panel of Fig. 5, it is also seen that the NN-FSI effect is small, not more than about 5 percent. This effect comes mainly from the change in the radial wave function of the final NN partial waves caused by the interaction. Therefore, it reduces the cross section. The charged final state $p\pi^-$ was investigated 30 years ago in a bubble chamber experiment

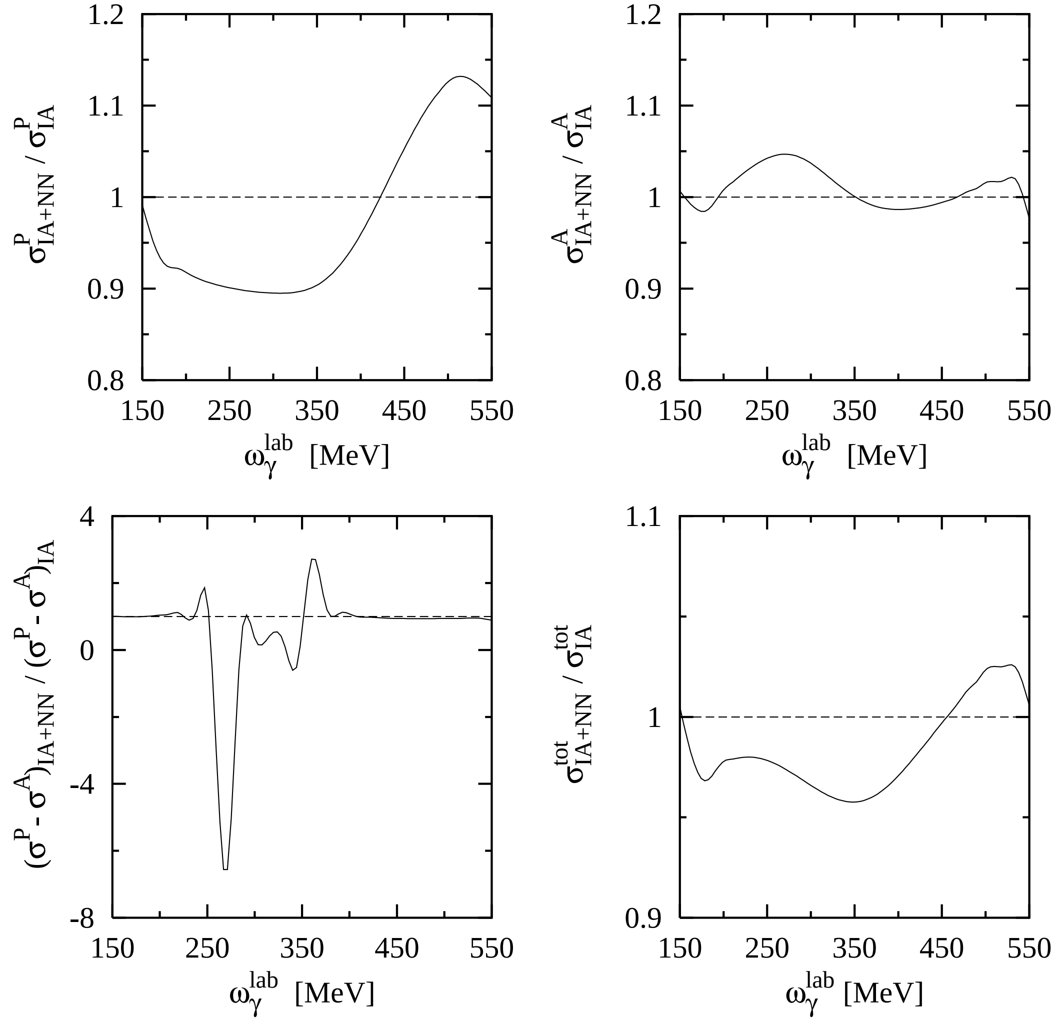

Fig. 6. The ratios $\sigma^P_{IA+NN}/\sigma^P_{IA}$ (upper left part), $\sigma^A_{IA+NN}/\sigma^A_{IA}$ (upper right part), $(\sigma^P - \sigma^A)_{IA+NN}/(\sigma^P - \sigma^A)_{IA}$ (lower left part) and $\sigma^{tot}_{IA+NN}/\sigma^{tot}_{IA}$ (lower right part) as functions of the photon lab energy.

on the $\gamma d \rightarrow pp\pi^-$ reaction by the ABHHM collaboration,[24] at Frascatti,[25] and later at higher energies by the TAGX-collaboration.[26] The bottom right panel of Fig. 5 presents a comparison between our results and this set of experimental data. It is readily seen that the inclusion of NN-rescattering considerably improves the agreement between the experimental data and the theoretical predictions.

§5. Summary and conclusions

We have investigated the influence of the NN-FSI effect on the polarized differential and total cross-section differences $(d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A$ and $\sigma^P - \sigma^A$, respectively, for parallel and antiparallel helicity states for the $\vec{\gamma}\vec{d} \rightarrow \pi^- pp$ reaction.

These helicity asymmetries give valuable information concerning the nucleon spin structure and allow a test of the GDH sum rule. For the elementary pion production operator from the free nucleon, we used an effective Lagrangian model. As the model for the interaction of the NN-subsystem, we used a separable representation of a realistic NN interaction, which gives a good description of the corresponding phase shifts.

The study of the polarized differential cross-section difference reveals that the reduction realized by including the NN-rescattering is 15% larger at pion forward angles. For pions emitted in the backward direction, the NN-rescattering effect is completely negligible. In comparison with experiment, quite satisfactory agreement is obtained. The polarized total cross sections for circularly polarized photons impinging on a target with spin parallel σ^P and antiparallel σ^A to the photon spin are also investigated. The contribution of $\vec{\gamma}\vec{d} \to \pi^- pp$ to the spin response of the deuteron has been explicitly evaluated over the range of the $\Delta(1232)$-resonance with inclusion of NN-rescattering. In the case of σ^P, we obtained a significant difference between the results for the IA and the elementary reaction, whereas for σ^A the difference is smaller. We found that NN-FSI effect appears mainly in σ^P. It leads to a strong reduction of the spin asymmetry in the energy region of the $\Delta(1232)$-resonance. This reduction becomes about 35 μb at its maximum. For the unpolarized total cross section, we found that NN-rescattering reduces the total cross section in the $\Delta(1232)$-resonance region by about 5 percent. In comparison with experiment, the inclusion of such an effect leads to improved agreement with the experimental data.

It remains as a task for further theoretical research to investigate the reaction $\gamma d \to \pi NN$ including a three-body treatment in the final πNN system. This extension is desirable for the calculation of such rescattering to help in further developments. Instead of a separable potential, a more realistic potential for the NN-scattering should be considered. A further interesting topic concerns the study of polarization observables with the inclusion of rescattering effects. Such studies should give more detailed information on the πNN dynamics and thus provide more stringent tests for theoretical models. As future refinements, we consider also the use of a more sophisticated elementary production operator, which will allow for the extension of the present results to higher energies. A measurement of the spin asymmetry for the deuteron is needed.

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